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Photon spectrum and polarization for high conversion coefficient in the Compton backscattering process

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ABSTRACT

This study looks to simulate the nonlinear Compton backscattering (CBS) process based on the Monte Carlo technique for the conversion coefficient $K_c \geqslant 1$, which can be considered as the average number of photons emitted by each electron. The characteristics of the nonlinear CBS process simulated in this work are as follows: the number of absorbed photons of a laser, the distance in the laser pulse in which the electron passes between two collisions, the energy and the polarization of the emitted photon in each collision, and the polarization of the electron before and after collision. The developed approach allows us to find the spectra and polarization characteristics of the final electrons and photons. When $K_c > 1$, the spin-flip processes need to be considered for a correct simulation of the polarization of the final photons and electrons for energies typical of a γ-γ collider.

1. Introduction

Following the discovery of the Higgs-like boson, the characteristics of various kinds of colliders are being considered for detailed study (e.g. a γ-γ collider with high luminosity [1,2]). The project SAPPHiRE [2] is expected to receive γ-beams in the scattering of laser photons with energies of $\hbar\omega_0 = 3.53$ eV by electrons with an energy of $E_0 = 80$ GeV, which produces γ-rays with a peak energy of $\hbar\omega \sim 65$ GeV. To achieve the desired luminosity (e.g. $L_{\gamma\gamma} \sim 3.6 \times 10^{33}\ \mathrm{cm^{-2}\ s^{-1}}$), the use of a laser with a peak power of $W_L = 6.3 \times 10^{17}\ \mathrm{W/cm^2}$ is assumed. The authors [2] have estimated the output of scattered photons, $N_\gamma = 1.2 \times 10^{10}$ photons/bunch, for an electron bunch population $N_e = 10^{10}$, for the following electron beam parameters: $\sigma_x \times \sigma_y = 400\ \mathrm{nm} \times 18\ \mathrm{nm}$; the degree of circular polarization of the laser photons, $P_c = -1$; and the longitudinal polarization of the electron beam, $P_e = 0.8$. The photon yield per an initial electron is characterized by the so-called conversion coefficient [3,4]:

$$K_c = N_\gamma / N_e, \tag{1}$$

where $N_\gamma = L_{e\gamma}\sigma$ is the number of scattered photons, $L_{e\gamma}$ is the luminosity characterized by the colliding laser and electron beams, and σ is the Compton scattering cross-section for a given energy of the laser photon $\hbar\omega_0$ and the electron with energy $E_0 = \gamma_0 mc^2$. The conversion coefficient for the project [2] achieves the value $K_c = 1.2$.

2. Theory

For the head-on collision between laser and electron bunches—which are described by three-dimensional Gaussian distributions with fixed parameters—the luminosity is calculated analytically and does not depend on the length of the colliding bunches [4]:

$$L = \frac{N_e N_L}{2\pi\sqrt{\sigma_{Lx}^2 + \sigma_{ex}^2}\sqrt{\sigma_{Ly}^2 + \sigma_{ey}^2}}. \tag{2}$$

In (2), $\sigma_{Lx(y)}$ and $\sigma_{ex(y)}$ describe the transverse sizes of the colliding beams (L and e indexes correspond to the laser beam and electrons, respectively); N_L is the total number of photons in the laser pulse; and β_0 is the speed of electrons in a bunch.

For the simplest case of azimuthally symmetric beams, ($\sigma_{Lx}^2 = \sigma_{Ly}^2 = \rho_L^2/2; \sigma_{ex}^2 = \sigma_{ey}^2 = \rho_e^2/2; \rho_L, \rho_e$ are the radii of the laser and electron beams at the interaction point) under the condition $\rho_e \ll \rho_L$ instead of Eq. (2), we obtain a simple formula:

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$$L \approx \frac{2N_e N_L}{\pi\rho_L^2}. \quad (3)$$

Thus, from the formulas (2) and (3), the conversion coefficient can be estimated, which depends on the length of the laser pulse (in other words, on the thickness of the light target [5]):

$$K_c = \frac{2N_L\sigma}{\pi\rho_L^2} = 2n_0\sigma\ell_L, \quad (4)$$

where $\ell_L = c\tau_L$ is the effective length of the laser pulse, and n_0 is the concentration of the laser photons.

The effective length of the laser pulse can be expressed in terms of the laser wavelength λ_0 and the number of periods N_0:

$$\ell_L = \lambda_0 N_0. \quad (5)$$

If the thickness of the light target is expressed through the so-called 'collision length',

$$\ell_c = \frac{1}{2n_0\sigma},$$

the Eq. (4) can be written as follows:

$$K_c = \ell_L/\ell_c.$$

The concentration of the laser photons n_0 at the interaction point is determined by the field intensity of the laser pulse

$$n_0 = \frac{a_0^2}{4\alpha\lambda_e^2\lambda_0} \quad (6)$$

Here, α is the fine structure constant, λ_e is the Compton wavelength of an electron, and a_0 is the laser strength parameter which can be estimated by the 'engineering' formula [6]

$$a_0 = 0.85\lambda_0[\mu\mathrm{m}]\sqrt{\frac{W_L[\mathrm{W/cm^2}]}{10^{18}}}, \quad (7)$$

where W_L is the laser intensity.

After substituting Eqs. (5) and (6) into (4), we obtain

$$K_c = \frac{\alpha}{2}a_0^2\frac{\sigma}{r_0^2}N_0. \quad (8)$$

Eq. (8) is based on the assumption of a constant cross-section along the trajectory of the electron in the light target. In this approximation, the conversion coefficient K_c is the mean number of collisions $\bar{k}$ of the initial electron with photons of the laser pulse. This approximation becomes incorrect if the electron experiences multiple collisions with laser photons, which would result in the loss of a significant part of its energy in each collision. As the energy of the electron decreases, the cross-section of the Compton scattering increases—and hence, the distance between two successive collisions in the light target decreases (see, for example, [7]).

The cross-section of the nonlinear Compton scattering, which depends on the parameter a_0, is the sum of the cross-sections $\sigma^{(n)}$, each of which describes the process:

$$p_0 + nk_0 = p_1 + k_1,$$

where the initial electron 'absorbs' n number of laser photons and emits one hard γ-quantum. Four momenta of the initial and final electron (photon) are designated as $p_0(k_0), p_1(k_1)$.

A detailed description of nonlinear Compton scattering with the polarization states of the initial and final particles is given elsewhere [8].

Based on equations from [8], we can write the cross-section of the nonlinear Compton scattering of polarized electrons with the spin-flip effect, and without taking into account the polarization of the scattered γ-quanta:

$$\frac{d\sigma^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} + \zeta_{0z}P_c\frac{d\sigma_2^{(n)}}{dy} + \zeta_z P_c\frac{d\sigma_2^{(n)}}{dy} + \zeta_z\zeta_{0z}\frac{d\sigma_3^{(n)}}{dy}, \quad (9)$$

where ζ_{0z} and ζ_z are the longitudinal polarization of the initial and final electrons, respectively, and P_c is the circular polarization of the laser photons. The cross-section $d\sigma_1^{(n)}/dy$ describes interaction of unpolazrized initial particles summarized over spin states of the final particles, the cross-section $d\sigma_2^{(n)}/dy$ describes interaction of polarized photons with polarized electrons, and the cross-section $d\sigma_3^{(n)}/dy$ describes interaction for the fixed polarization states of the inital and final electrons (see formula (32) and (33) in [8]).

In Eq. (9), standard variables are used:

$$x_0 = \frac{2p_0k_0}{(mc^2)^2} = \frac{4\gamma_0\hbar\omega_0}{mc^2},$$

$$y = \frac{k_0k_1}{p_0k_0} = \frac{\hbar\omega}{\gamma_0 mc^2} = \frac{\hbar\omega}{E_0}.$$

The last expressions were obtained by the ultra-relativistic approximation.

The maximum value of the variable y in the reaction involving n number of laser photons is determined by the following condition:

$$y = y_{\max}^{(n)} = \frac{nx_0}{1 + nx_0 + a_0^2/2}. \quad (10)$$

Cross-sections $d\sigma_i^{(n)}/dy$ can be calculated using expressions presented elsewhere [8].

The cross-section without spin-flip for the considered photon polarization state $P_c = -1$ is defined as:

$$\frac{d\sigma_{11}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} - 2\frac{d\sigma_2^{(n)}}{dy} + \frac{d\sigma_3^{(n)}}{dy} \quad (11)$$

for the transition $<\zeta_{0z}> = +1 \rightarrow \zeta_z = +1$, and

$$\frac{d\sigma_{22}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} + 2\frac{d\sigma_2^{(n)}}{dy} + \frac{d\sigma_3^{(n)}}{dy} \quad (12)$$

for the transition $<\zeta_{0z}> = -1 \rightarrow \zeta_z = -1$.

From Eq. (9), we obtained the cross-section for the spin-flip process; it is the same as for both kinds of transitions $1 \rightarrow 2$ and $2 \rightarrow 1$:

$$\frac{d\sigma_{12}^{(n)}}{dy} = \frac{d\sigma_{21}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} - \frac{d\sigma_3^{(n)}}{dy}. \quad (13)$$

See, for instance, Fig. 1, where the spin-flip cross-section is presented for $n = 1$. One can see that such a cross-section can achieve about 40% from the cross-section without spin-flip for our case $E_0 = 80$ GeV.

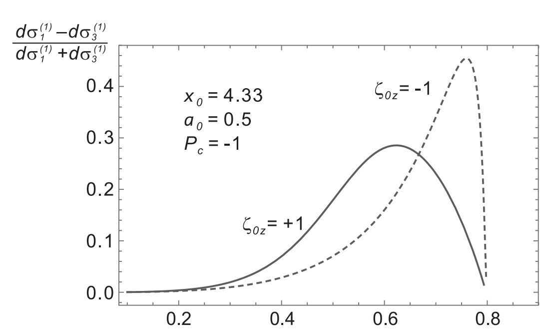

Fig. 1. Spin-flip cross-section, calculated for $n = 1, k_0 = 4.33$ and $a_0 = 0.5$.